Mining the Hydrogen Peroxide of Mars for Monopropellant Rocket Fuel

Francisco J. Arias*
Department of Fluid Mechanics, University of Catalonia, ESEIAAT C/ Colom 11, 08222 Barcelona, Spain

Already since the 1970s, hydrogen peroxide (H_2O_2) has been suggested as a possible oxidizer of the Martian surface, but until only three decades latter it was finally detected. So far, the interest aroused by planetary scientist on H_2O_2 is because it could be the key catalytic chemical that controls Mars atmospheric chemistry. However, from the point of view of a rocket scientist hydrogen peroxide is a rocket fuel, and indeed it is the most simple monopropellant rocket fuel known. Here, a scoping study was made for the possibility of mining the hydrogen peroxide from the regolith or from the atmosphere of Mars to be used as monopropellant rocket fuel. Although certainly with a rather reduced low specific impulse and then a limited transfer of momentum to the spacecraft for each unit of propellant expended, nevertheless, H_2O_2 offers an interesting alternative for the red planet in terms of its availability, simplicity and reliability. Two methods were investigated, namely. (1) by mining H_2O_2 directly from the regolith, and (2) by the continuous removal from the atmosphere. It was found that the first option seems unpractical -at least for the early stages of human expedition, because will require vast amounts of regolith to be removed, processed and dumped owing to the poor concentration in the martian regolith. Nevertheless, pumping out the atmospheric H_2O_2 will allow to obtain the required propellant for a Mars Ascent Vehicle (MAV) during the length of time in which the expedition must remain on Mars - Hohmann orbital rendezvous, and with a reasonable area of collector as well as input pumping power. Pumping power driven by photovoltaic energy sources, radioisotope generators (RTGs) were briefly investigated.

Keywords. *Mars exploration; Mars Ascent Vehicle (MAV); Rocket fuel; Low Mars Orbit (LMO); In situ resource utilization (ISRU)*

I. INTRODUCTION

Despite hydrogen peroxide H_2O_2 has been suggested as a possible oxidizer of the Martian surface since the Viking mission in 1976 [1], [2], nonetheless the search for H_2O_2 was unsuccessful for more than two decades and only until 2003, hydrogen peroxide was finally detected [3]. Hydrogen peroxide on Mars has been suggested as a key catalytic chemical that controls Mars atmospheric chemistry[4], however, from the point of view of rocket technology, hydrogen peroxide is also a rocket fuel, and indeed it is the most simple monopropellant rocket fuel known. The object of this scoping work was to explore the possibility of mining the hydrogen peroxide from the regolith or from the atmosphere of Mars with the aim to be used as monopropellant rocket fuel.

II. STATEMENT OF THE CORE IDEA

The use of hydrogen peroxide as a monopropellant in rocketry goes back to some of the earliest German experiments, who successfully used somewhat impure solutions of 80 to 85 per cent H_2O_2 by weight, [5].[6]. Fundamentally, in a hydrogen peroxide rocket, the H_2O_2 is concentrated up to a fairly stable 90% purity and then when passed over a metallic catalyst it will decompose to water and oxygen, along with an amount of heat, [7]. Because the advantages of using hydrogen peroxide related with its simplicity and reliability, several applications were promptly found for H_2O_2 as for example: as source of power for helicopters , for propelling models, for submarine propulsion, and rocket -assisted take-off units, just to name a few, [8].

• Hydrogen Peroxide on Mars and its feasibility as Rocket Fuel

Although the production of H_2O_2 on Mars is believed to be mostly by photochemical process in the atmosphere which is consistent with the discovery in the last decade of H_2O_2 at 20-40 ppb volume on Mars, [9], nevertheless the soil reactivity implied by the Viking results indicate levels ranging from at least 1 ppm, [10] up to $\sim$250 ppm,[11]. It has been suggested in the last years that one additional source of hydrogen peroxide could be by atmospheric electrical discharges during dust storms, [12]. By the aforementioned, the feasibility of hydrogen peroxide of Mars as monopropellant rocket fuel must be addressed

*Corresponding author: Tel.: +32 14 33 21 94; Electronic address: francisco.javier.arias@upc.edu

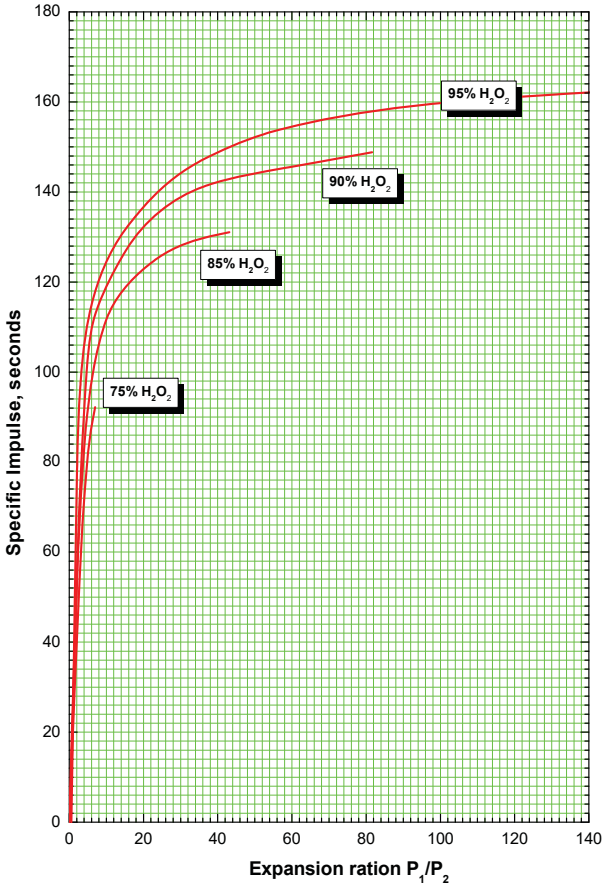

FIG. 1: specific impulse *vs.* expansion ratio for 75 to 90% H_2O_2 and considering expansion to saturation point,[8].

not in terms of its existence (which is already confirmed) but in terms of the feasibility to obtain the amount required as propellant during the expedition time. In order to get a first estimate on the mass of peroxide required for the a specific manoeuver, for example, to transfer a Mars Ascent Vehicle to Low Mars Orbit, we can proceed as follows.

To begin with, the amount of propellant m_p (hydrogen peroxide in our case), which is required to lift a spacecraft with a total dry mass M_o (total mass of the spacecraft minus propellant which includes crew, payload, etc...) and moving under the action of a downward pull planetary gravity and neglecting the atmosphere resistance can be calculated by well rocket equation, [13]

$$m_p \approx M_o \left[e^{\frac{u}{u_e}\frac{n+1}{n}} - 1 \right] \qquad (1)$$

where $n \times g$ is the spacecraft acceleration being g the gravity of the planet, and then n a dimensionless quantity representing the ratio of spacecraft acceleration to the planetary gravity. The value of n is not likely to exceed 5 to 10 for unmanned missions [13], but for manned missions considering that on average human can withstand up to 4-6 g -exceptionally fighter pilots can manage perhaps up to about 9g but only for a second or two, but for sustained g-forces 6g would be fatal and therefore a safety factor should be $n \sim 3$ or thereabouts; u_e is the exhaust velocity; and u is the velocity Δ u-budget for the specific manoeuver (e.g., for escape, Low Mars Orbit, etc...).

The exhaust velocity u_e attainable by the hydrogen peroxide is strongly dependent with the concentration as can be seen in Fig. 1 where the specific impulse is shown against expansion ratio for concentrations between 75 to 90% H_2O_2 and considering expansion to saturation point, [8]. It is seen that for the most optimistic case an 160-sec ISP or around ~ 1.6 km/s could be attained by using highly purified concentration. Fig. 2 shows the $\frac{m_p}{M_o}$ calculated form Eq.(1) as function of the u-budget of the specific manoeuver for Mars and assuming a 160-sec ISP with $n = 3$, i.e., with an acceleration three times greater than planetary gravity. It is easy to see, that owing to the low specific impulse of the propellant an escape manoeuver may require vast amounts of peroxide ($\frac{m_p}{M_o} \sim 65$), however for a Low Mars Orbit (LMO), the figure drops within the limits of practical application for a , say, a Mars Ascent Vehicle MAV ($\frac{m_p}{M_o} \sim 26$).

III. METHODS FOR HARVESTING THE REQUIRED H_2O_2 OF MARS FOR MONOPROPELLANT ROCKET FUEL

After having obtained in the preceding section a preliminary figure for the amount of H_2O_2 required, now it is necessary to asses the feasibility to obtain this amount either from the regolith or from the atmosphere of Mars during the time scale of the expedition. This time for a Hohmann orbital rendezvous is about to years and eight months which is needed for a round-trip in order to allow that the planets realigned themselves properly so that the Earth would be present at the time the returning spacecraft was crossing the Earth´s orbit,[17].

There are at least two methods by which H_2O_2 can be harvested from Mars, namely. First by direct mining of the regolith, i.e, farming the peroxide which can be found already in the soil. Second by continues atmospheric removal before the peroxide fall into the soil.

- **Method I: Mining the Martian regolith**

The first method by which the H_2O_2 could be harvested is just by direct mining of the regolith. Nevertheless, even assuming the most optimistic concentrations of the hydrogen peroxide detected at the Viking site (~ 250 ppm), mining the regolith will require a vast amount of material to be removed from the soil and then into a large plot of mining land in order to obtain the amount of necessary propellant. In addition, the regolith should be transported, filtered and dumped with the extreme climatological conditions of the red planet and during the limited time of the expedition. For the sake of

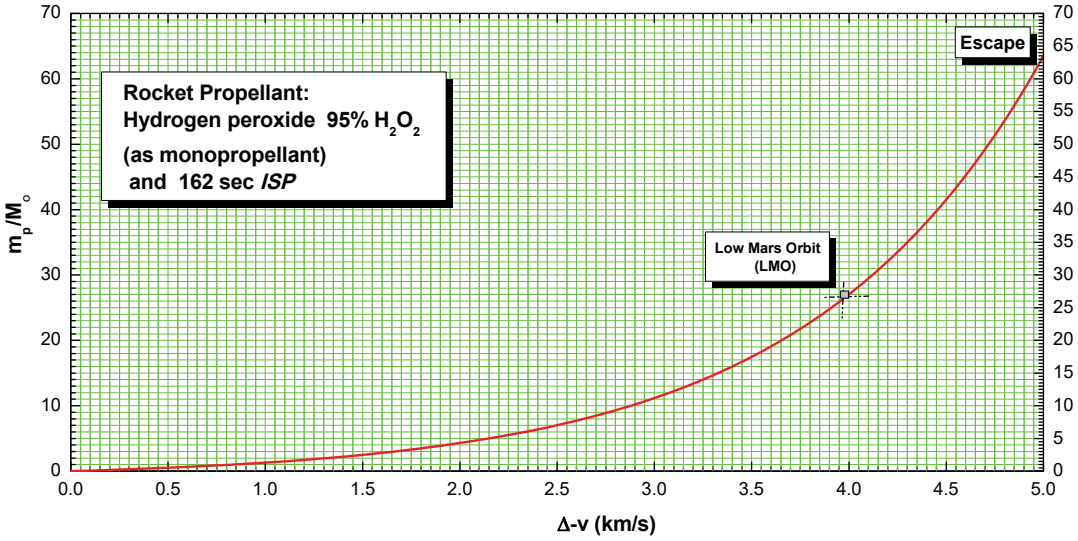

FIG. 2: $\frac{m_p}{M_o}$ as function of the Δ-v budget of the specific manoeuver for Mars using H_2O_2 as rocket fuel monopropellant.

illustration, let us consider the following example: from our previous analysis in order to lift a MAV spacecraft to LMO it will require a propellant-dry mass ratio around $\frac{m_p}{M_o} \sim 26$, so, if one considers a six-crew MAV , it has to carry more than 500 kg -if one considers a 82.2 kg for a 50th percentile male crew member,[15], and thus the total amount of H_2O_2-propellant required will be $> \frac{m_p}{M_o} \times 500$kg or about, 13 ton of H_2O_2 which must be extracted from the regolith during the expedition time ()at least during the erly stages of human expeditions. Now, considering a concentration of H_2O_2 in the martian soil around 20-40 ppb volume,[4], a regolith density 1.52 g/cm^3, [16], (implying a bulk regolith porosity of 60 ± 15 %), a peroxide density 1.45 g/cm^3, then, 13 tons of H_2O_2 will require the removal of above, 0.3 Gt (gigatonne) of regolith which is clearly impractical. Even assuming a much more optimistic figure for the concentration of peroxide around ∼ 250 ppm, as was found at Viking site, the figure will drops in the order of ∼ 1 Mt (megatonne) which is still impractical, where it must be kept in mind that all the regolith not only must be removed but also precessed and dumped.

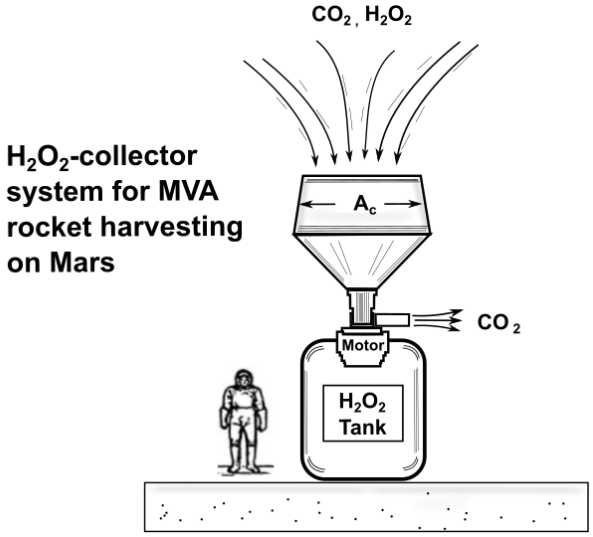

FIG. 3: Scheme of a possible atmospheric H_2O_2 collector for production of propellant rocket fuel for MAVs.

• Method II: Obtaining H_2O_2 by pumping out from the atmosphere.

The problem of working with a vast amount of solid material imposed by the direct mining of the martian regolith may be overcome by pumping out the H_2O_2 directly from the martian atmosphere. This strategy not only prevents the lost of H_2O_2 by absorbtion and catalytic destruction upon diffusing into the soil, but also the continuous processing during day and night H_2O_2 by just pumping out the Martian air from the atmosphere, where seems that there is not the least objection that it is incomparably much more easy collect H_2O_2 by pumping continuously air from the atmosphere and exhausting the depleted air into the same atmosphere rather than the removal of solid material from the soil. In addition, because the process can be performed continually just by running a turbine during day and night,this will translate in a very vast amount of air processed at the end of the expedition. Fig. 3 is a sketch which although admittedly oversimplified, nonetheless illustrates the essence of the idea.
In this device, a large amount of air is pumped out continuously from the atmosphere, peroxide is continually separated, and residual air (depleted in H_2O_2) exhausted. For this scheme, there are two fundamental

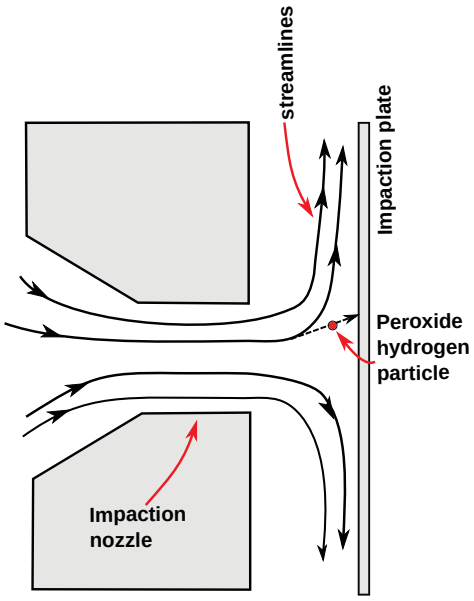

FIG. 4: Inertial impactor for separation of particles being transported by gases

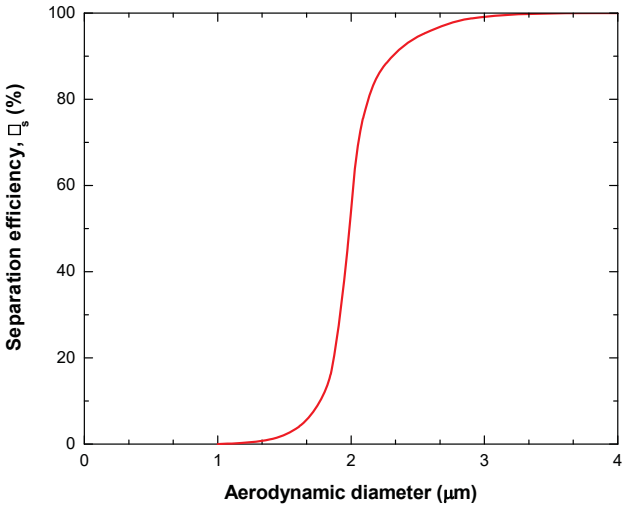

FIG. 5: Typical impactor efficiency curve. From [19]

aspects which must be preliminary considered. On one hand, the pumping power required to move the air, i.e. the input power of the turbine, and on the other hand, a suitable method for the continuous separation of peroxide from the air.

As regard to the separation of H_2O_2 from the air, several techniques can be a priori envisaged by almost certainly all of them will based on the physical separation of H_2O_2 from the air accounting by the lower solidification temperature of H_2O_2 in comparison with CO_2. In fact, near the ground because the low temperatures H_2O_2 condense (with the formation of condense nuclei) into falling snow and then could be easily separated from CO_2. Then a possible technique for H_2O_2 separation from the air stream could be by aerosol impaction which is the process in which aerosol particles (in our case the condensed nuclei of H_2O_2) can be removed from an air stream by forcing the gase to make a sharp bend as schematically depicted in Fig. 4. The particles of peroxide once have been removed from the stream can be properly collected. Other systems for the continuous separation of H_2O_2, for example, could be using a fractionating column in which the air stream is cooled and then peroxide separated which also is based on the differences in volatility. Concerning the pumping power requirement, a preliminary assessment can be performed as follows:

Let us assume, a simplified atmospheric removal and collector system as was sketched in Fig. 4. If we assume that the atmosphere is an infinite reservoir of H_2O_2 with a constant concentration c_a, then the total net flux crossing the collector J_c is given by

$$J_c = c_a v_t \tag{2}$$

where c_a is the atmospheric concentration of H_2O_2 (particles per unit volume) and v_t is the pumping velocity. Taking into account that the pumping power W is given approximately by

$$W \approx \frac{\rho v_t^3 A_c}{2} \tag{3}$$

where ρ is the density of the atmosphere; and A_c the area of the collector. By inserting Eq.(3) into Eq.(2) one obtains,

$$J_c = c_a \sqrt[3]{\frac{2W}{\rho A_c}} \tag{4}$$

The total number of particles of hydrogen peroxide N_p crossing the collector is obtained by integrating the flux expression of Eq.(4) over the cross section area A_c and with the time

$$N_p = J_c \times t_c \times A_c$$

$$= c_a t_c \sqrt[3]{\frac{2W A_c^2}{\rho}} \tag{5}$$

where t_c and A_c are the total time for collection and the area of the collector, respectively. Therefore, by knowing

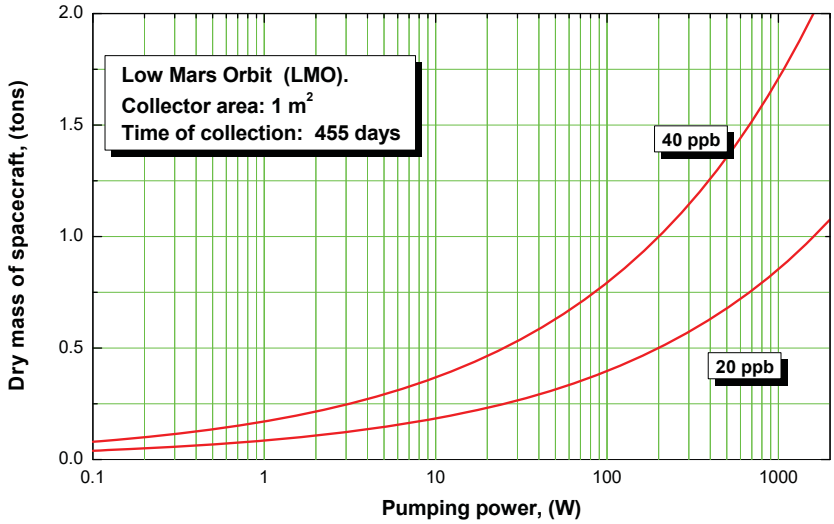

FIG. 6: Pumping power as function of the total dry mass of MVA for a concentration of H_2O_2 40 ppb and 20 ppb in the atmosphere

the time of collection, t_c; the area of the collector A_c; the density of the air ρ and the pumping power W it is possible to know the number of particles of H_2O_2 crossing the collector area if one knows the concentration of particles of peroxide per unit volume c_a. The concentration c_a can be expressed as function of the concentration ppm or ppb in the atmosphere as $c_a = \frac{ppm}{V_p} \times 10^{-6}$ or $c_a = \frac{ppb}{V_p} \times 10^{-9}$, respectively, where V_p is the volume of a particle of peroxide. In the same way, the total mass of peroxide m_p is given by $m_p = N_p \times V_p \times \rho_p$ where ρ_p is the density of the peroxide. Thus, putting all together Eq.(5) becomes

$$m_p = \rho_p t_c \sqrt[3]{\frac{2WA_c^2}{\rho}} \times ppm \times 10^{-6} \qquad (6)$$

or

$$m_p = \rho_p t_c \sqrt[3]{\frac{2WA_c^2}{\rho}} \times ppb \times 10^{-9} \qquad (7)$$

for the concentration in ppm or ppb, respectively.

Eq.(6) and Eq.(7) give us the total mass of peroxide being continuously transported by the air stream, i.e., being pumped by the turbine. However, the effective number of particles of peroxide being collected will depend on the efficiency of the specific separation system used. If we define an efficiency coefficient for the separation ϵ_s, then, the effective mass of peroxide collected is given by

$$m_p^* = m_p \times \epsilon_s \qquad (8)$$

Thus, in order to asses the capability of collection of H_2O_2 it is necessary to know the separation efficiency ϵ_s which, of course, depends on the specific separation system used (e.g., fractionating columns, inertial impactor, etc...). Nevertheless, the separation efficiency could be very high if one consider the inertial impaction method as shown in Fig. 4. In fact, the separation efficiency by inertial impaction approaches $\epsilon_s = 100\%$ when particles are with diameters larger than 2 μm as is shown in Fig. 5, [19]. It is reasonable to assume that the peroxide of hydrogen snowing from the ski towards the surface of Mars attain diameters at least in the micrometer range, and in any case the growth of particles of H_2O_2 (acting as condensation nuclei) can be promoted by a cooling system. By the same token, it is expected that the efficiency of separation could be higher when the environment temperature is lower (because the peroxide particles will grow), i.e., during winter and the nights. Nevertheless, by looking at Fig. 5 and for preliminary assessment, it can be taken $\epsilon_s \approx 100\%$ and then $m_p^* \approx m_p$.

•Discussion

To obtain some idea of the area of collector needed as function of the mass of the spacecraft for a surface-to-LMO transfer, we assume some typical values of the parameters: atmospheric concentrations of H_2O_2 from 20-40 ppb volume on Mars, [9], although much more larger concentrations were observed by the Viking results (see Appendix); an atmospheric density $\rho = 10^{-2}$ kg/m^3 and peroxide density $\rho_p = 1.45 \times 10^3$kg/m^3; a length of time in which the expedition must necessary remain on Mars for Hohmann orbital rendezvous $t = 455$ days; a practical area of collector $A_c = 1$ m^2. The resulting curves are shown in Fig. 6 for the pumping power required to transfer the spacecraft with a dry mass M_o to LMO. It is seen that for the most conservative assumption of 20 ppb pumping powers between 200 W

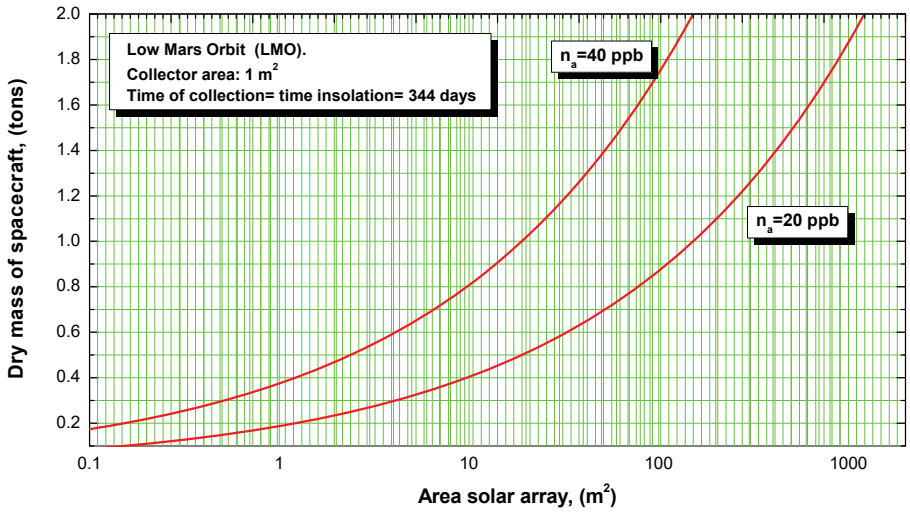

FIG. 7: Total dry mass of MVA as function of the solar array area

o 2000 W seems to be required for MAVs with masses between 0.5 to 1 tons, respectively.

IV. PUMPING POWER SOURCES

As regard the source of energy available, there are at least two sources which deserve a special mention, namely. Solar power and nuclear power from radioisotope thermoelectric generators.

• Photovoltaic arrays

If the source of energy is photovoltaic, then the available pumping power W in Eq.(5) is given by

$$W = I \times A_s \times \epsilon \tag{9}$$

where I is the solar isolation on Mars, A_s the area of the solar array; and ϵ is the efficiency of the solar array. Assuming a typical GaAs solar cell with an efficiency $\sim 20\%$ at Mars, and a global insolation on a horizontal surface as recorded from the Viking Lander 1 which averages around ~ 125 W/m^2 per day during the spring and summer,[18], we obtain Fig. 7 which shows the dry mass of the spacecraft to transfer at LMO as function of the solar array area and running the system only during the spring and summer (when atmospheric dust content is lowest). It is seen, that for MAVs around 0.5 to 1 ton of weight, and considering 20 ppb of concentration a solar array with an area of 20 to 160 m^2 is required, respectively. This area is within the realistic capability for a early expedition on the red planet.

• Radioisotopic Thermoelectric Generator (RTG) as power source

Another option is by the use of radioisotopic thermoelectric generators or RTGs. In this case, the thermal power generated from ^{28}Pu -as the most suitable radioisotope, is around 0.568 W per gram. Unfortunately thermoelectric modules, though very reliable and long-lasting, have very poor efficiencies around 3-7%. So, assuming an average value of 5% we have $\sim$ 28 W per kilogram of ^{28}Pu. Fig. 8 shows, the dry mass of the spacecraft to be transferred to LMO as function of the mass of ^{28} Pu required. According with this figure, for an average concentration 30 ppb around 5 kilograms will be required for a MAVs around 0.5 ton. By comparison, the Curiosity´s RTG is fueled by 4.8 kg of ^{28}Pu dioxide.

V. APPENDIX

In preceding sections it was considered hydrogen peroxide concentrations around 20 to 40 ppb, as discovered in the last decade [9], which are consistent with photochemical process generation in the atmosphere. nevertheless the soil reactivity implied by the Viking results indicate levels ranging from at least 1 ppm, [10] up to $\sim$250 ppm,[11]. One additional source of hydrogen peroxide is by atmospheric electrical discharges during dust storms, [12]. This hypothesis seems plausible in view of the last years laboratory studies, desert fields tests , and numerical simulations which indicate that the aeolian dust transport can generate atmospheric electricity by contact electrification (triboelectricity), [20]. If such large concentrations can be found on Mars, then the amount of H_2O_2 which can be removed from the atmo-

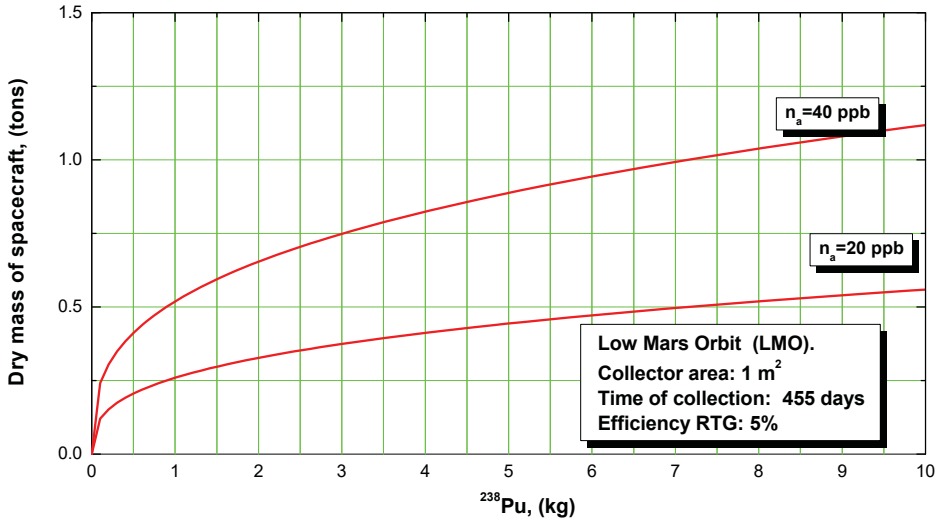

FIG. 8: Total dry mass of MVA as function of the mass of ^{28}Pu of the RTG.

sphere of Mars calculated previously will be drastically dropped if one considers that the new concentration is several orders of magnitude higher.

VI. SUMMARY OF RESULTS AND CONCLUSIONS

In this work, consideration was given on the feasibility for mining the hydrogen peroxide (H_2O_2) of Mars to be used as monopropellant rocket fuel. It was found that by direct atmospheric removal of H_2O_2, the required amount required for propellant can be collected during the time expedition compatible with a Hohmann orbital rendezvous to transfer to low Mars orbit a medium Mars Ascent Vehicle MAV of 0.5 to 1 ton weight. Pumping power sources were explored and it was found that solar photovoltaic arrays will require the use of solar arrays between 20 to 160 m^2, and radioisotope thermoelectric generators around $\sim$ 5kg of ^{28}Pu, both figures seems technically feasible.

NOMENCLATURE

c = concentration of H_2O_2, m^{-3}
g = gravitational acceleration, ms^{-2}
I = solar irradiation, Wm^{-2}
J = particle cross sectional flux, $s^{-1}m^{-2}$
m_p = mass of H_2O_2 rocket fuel, kg
Mo = dry mass of the MAV, kg
n = dimensionless ratio spacecraft acceleration to planetary gravity
N = number particles
t = time. s
v_e = exhaust velocity, ms^{-1}
W = pumping power, W

Greek symbols

ρ = density, kg m^{-3}
ϵ = efficiency separation coefficient

subscripts

a = atmospheric
c = collector
p = particle, peroxide
s = soil, separation

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